EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — AB DEPARTMENT

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Design of the 2 MHz, 100 kW Amplifier for the 3 MeV, H^- Source

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Abstract

Design and simulations of the 100 kW, 2 MHz amplifier required for the 3 MeV test stand H^- source, the future Linac 4 and possibly the SPL.

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1. GENERAL CONSIDERATIONS

This amplifier is meant to heat the hydrogen plasma of the H^- source required for the 3 MeV, test stand and, in future, the Linac 4 and possibly the SPL. Energy is inductively transferred to the plasma by a coil that is suspended from ground and sits at ~ 100 kV. From the specifications (Table 1) we see that the power amplifier has to supply a peak power of 100 kW but the duty cycle is low. In the case of operation in the 3 MeV, test stand, the 1 ms RF burst is repeated at 2 Hz (duty-cycle 0.2 %). In future the repetition rate is expected to increase drastically to 50 Hz bringing the duty-cycle to 5 %. The following design is based on this last figure so that the duty cycle increase will only require upgrading of the power supplies and cooling.

Table 1 – Main amplifier specifications

Frequency	Tunable at 2 ± 0.2 MHz
Bandwidth	≥ 10 kHZ
Output power	100 kW
Input / output impedance	50 Ω
Pulse length	1 ms
Repetition rate	2 Hz ≡ 3MeV Test Stand 2 Hz ≡ Linac 4 50 Hz ≡ SPL
2nd and 3rd harmonic component	<20 dBc

Among the different tubes available on the market, the Thales RS1084CJ seems to be well suited for this task. It has already been proved that it can reliably provide peak power in excess of 200 kW (AD bunch rotation system driver) and is widely used in the PS complex.

2. ANODE CIRCUIT

From the constant current curves of the selected tube it can be seen that at:

$$V_{G-K}=0\ V,\ V_S=1500\ V \text{ and } V_A=3\ kV \quad \equiv I_{AM} \geq 40\ A.$$

In first approximation, for Class C operation and high Q resonant anode circuit, the expected first harmonic component of the anode current is:

$$I_A \sim I_{AM} / 2 = 20\ A.$$

Therefore to achieve the required power the peak plate voltage swing and load are:

$$V_A = P_{OUT} / I_A = 2{\cdot}10^5 / 20 = 10\ kV \qquad\qquad R_A = V_A / I_A = 500\ \Omega$$

To allow some margin for the achievable output power, the anode load has been set at:

$$R_A = 700\ \Omega$$

The impedance transformation of the load $R_L=50\ \Omega$ into the required anode resistance $R_A = 700\ \Omega$ is achieved using a transformer made from coaxial cable. This allows a practical and compact implementation of the anode RF choke. The tube output capacitance, measured to be $C_A{\sim}80\ pF$ including the socket and overall circuitry, is resonated at 2 MHz by the transformer inductance ($79.2\ \mu H$). About half of this value is due to the tube and the rest comes from the physical component layout. The anode resonator Q value is low ($Q{\sim}\omega{\cdot}C_A{\cdot}R_L{\sim}0.7$) so that small variations in tube capacitance will not require re-tuning of the anode circuit.
The anode transformer physical dimensions do not allow the achievement of unit coupling factor among the coils. The equivalent circuit includes therefore a non-negligible leak inductance that has also to be compensated. The overall equivalent anode circuit is shown in figure 1 together with the measured and simulated response.

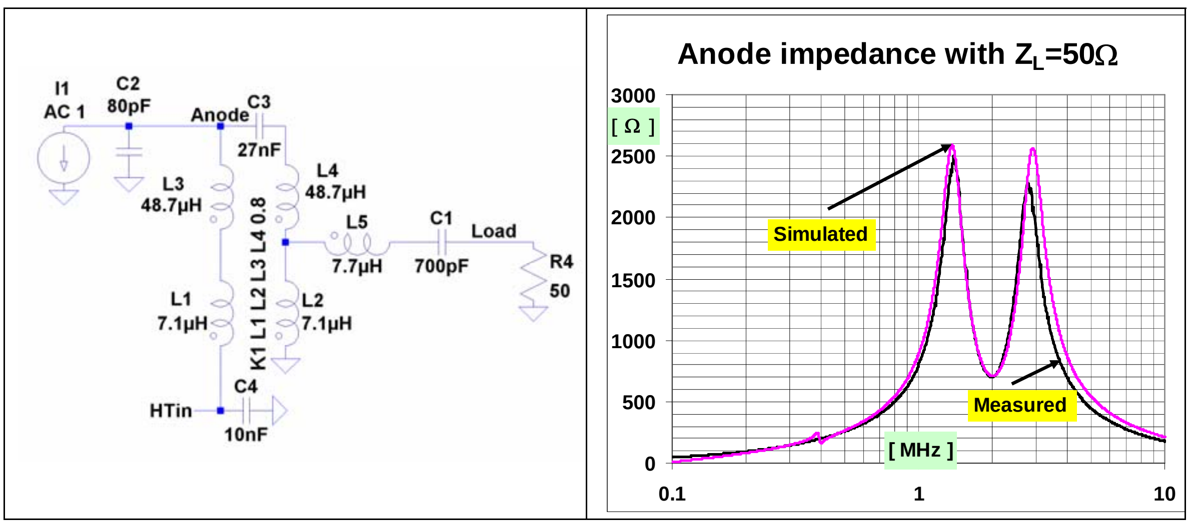

Figure 1 – Anode circuit

The DC blocker and HT input filter is made with 2 nF, 30 kV capacitors. 13 units are used for the DC blocker and 5 units for the HT filter.

3. Grid circuit

The tube input capacitance, including the socket, is

$$C_{IN} \sim 450\ pF$$

Considering the miller effect, the best resonant conditions found with Spice simulations imply the use of a 13 µH inductor. This inductor is also used to implement a 1 to 3 input transformer to match the 50 Ω input to a grid de-Qing resistor

$$R_G \sim 450\ \Omega$$

Using 4C65 ferrite cores (23.6X13.4X5.1 mm, $S = 2.6 \cdot 10^{-5}$ m^2, Al = 0.087 µH/n^2) and limiting the induction to $B_{Max} \leq 35$ mT the product **N**umber of cores x **n**umber of turns required for 210 Vpeak excitation and 2 MHz is

$$N\ x\ n \geq 18$$

Using three stacked cores, 6 turns on the high impedance side and 2 turn on the low impedance side the impedance transformation ratio and B_{Max} conditions are respected with an inductance slightly lower than required leaving the possibility of retuning the circuit by adding a 200 pF capacitor.
The drive power for maximum output and class AB operation (V_{GBIAS}=-210 V, I_{Ao}= 6 A) is then limited to

$$P_{IN} = 210^{\wedge 2}/(2 \bullet 450) \sim 50\ W$$

4. SIMULATED OVERALL RESPONSE

The amplifier simplified schematic is shown in figure 2. The tube model, derived from constant current curves and listed in figure 3, nicely agrees with published data as shown in Table 2 where I_A vs. V_G at different V_A are listed.

Table 2 – Comparison of data sheets and spice model of tube

	V_A = 3 kV		V_A = 10 kV		V_A = 15 kV	
V_{G-K} [V]	I_A simulation [A]	I_A data sheets [A]	I_A simulation [A]	I_A data sheets [A]	I_A simulation [A]	I_A data sheets [A]
-340	0.04	0	0.16	0	0.25	0
-300	0.1	0	0.4	0.2	0.6	0.5
-200	3.5	3	5.6	6	7	8
-100	19	20	24	25	28	28
-40	31	32	37	38	41	41
0	40	41	46	48	50	52

With 18 kV HT anode supply, simulations give an output power of 130 kW with the tube biased in Class AB (V_{GBIAS}=-210 V, I_{Ao}= 6 A and V_{RF}=200 V). The HT supply current is then:

$$I_{HT} \sim 16\ A$$

If we assume that this current is supplied by an energy storage capacitor during 1.2 ms and a voltage drop of 1000 V is allowed, the minimum required capacitance is:

$$C_{HT} \sim 20\ \mu F$$

For 2 Hz and 50 Hz repetition rate the power supply shall thus provide the following average currents:

40 mA @ 2 Hz - 1 A @ 50 Hz

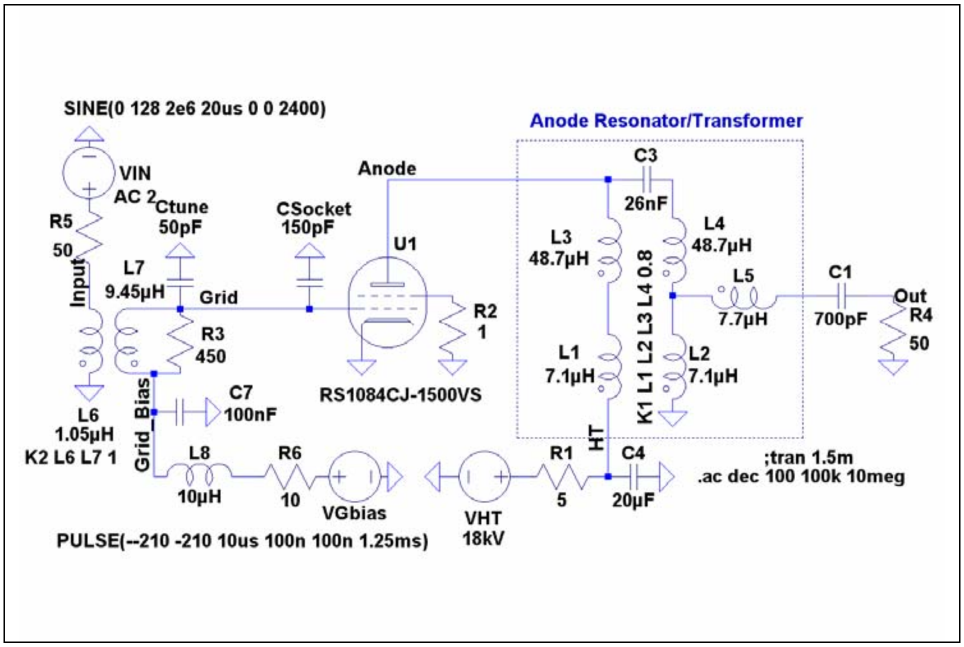

Figure 2 – Amplifier simplified circuit

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*RS1084CJ with 1500v Ug2
.SUBCKT RS1084CJ-1500VS 10 20 30 50 ;(CATH GRID ANODE SCREEN)
*I sources for cath.,screen,grid,anode as fn(Vg,Va)---------
Gk 40 14 value = {v(2,10)*(V(1,10)+(V(30,10)/V(3,10)))};cathode
Gs 50 15 value = {v(4,10)*v(5,10)*v(2,10)};screen I
Gg 20 12 value = {v(6,10)*1};grid I
Ga 30 13 value = {v(2,10)*(i(vmk)-i(vms)-i(vmg))};anode I
*tables(construct from constant I curves) ------------
*E1=sum Is+Ia+Ig (=Ik) as fn Vg at Va=0---------
E1 1 10 table {V(20,10)} = (-290,0) (-250,0.5) (-210,2) (-175,5) (-145,10) (-85,20) (-40,30) (5,40) (45,50) (85,60) (130,70) (175,80)
*E3=gives slope of Ik with Va for different Vg when substit. in Gk-----
E3 3 10 table {V(20,10)} = (-500,50meg) (-320,200k) (-300,25K) (-240,6k) (-220,4400) (-160,2000) (-140,1500) (-40,1300) (130,1100)
*E2 truncates all I for -ve Va -----------
E2 2 10 table {V(30,10)} = (30,0) (100,1)
*E4 & E5 decribe Is as fn(Va,Vg=0v) & (Is as multip f(Vg,Va=.5kV) ---------
E4 4 10 table {v(30,10)} = (1100,12) (1200,8) (1700,4) (2300,2) (3300,1) (4.8K,0.5) (10k,.2)
E5 5 10 table {v(20,10)} = (-290,0) (-270,0.025) (-250,0.0625) (-210,0.125) (-170,0.25) (-100,0.05) (0,1) (100,1.5)
*E6=grid I as fn(Vg)
E6 6 10 table {v(20,10)} = (0,0) (10,.5) (20,1)
*Electrode capacitances
Ckg2 10 50 12pF
Cka 30 10 0.3pF
Cag1 30 20 1.9pF
Cg1k 20 10 136pF
Cg1g2 50 20 165pF
Cag2 30 50 43pF
* Dummy resistors across table nodes
Rd1 1 10 1MEG
Rd2 2 10 1MEG
Rd3 3 10 1MEG
Rd4 4 10 1MEG
Rd5 5 10 1MEG
Rd6 6 10 1MEG
Rd40 40 10 1
Rd50 50 10 1MEG
* I meas.voltmeters
Vms 15 10 0
Vmk 14 10 0
Vma 13 10 0
Vmg 12 10 0
.ENDS
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Figure 3 - RS1084 model for VS=1500 V

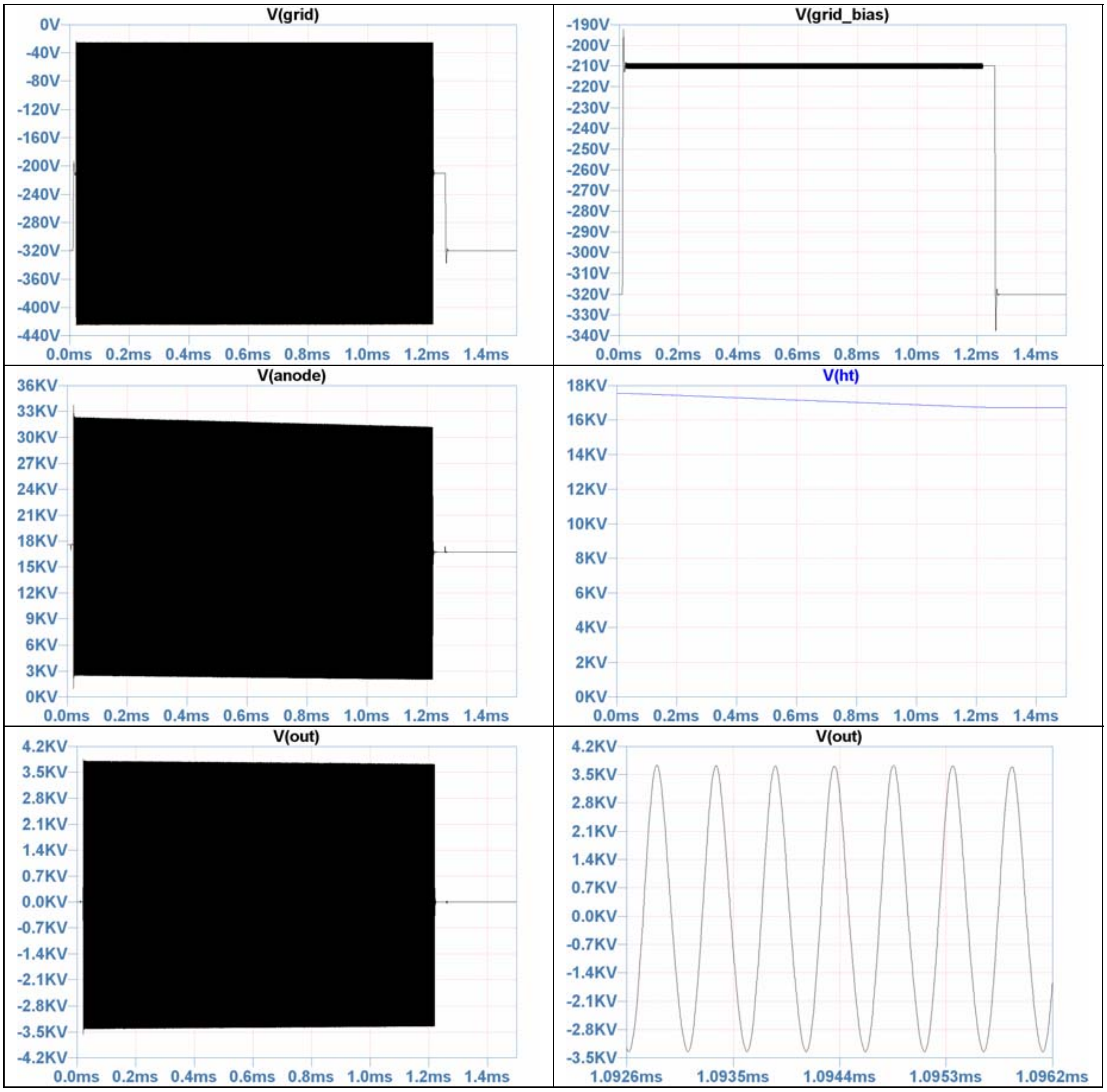


Figure 4 – Time domain simulation results

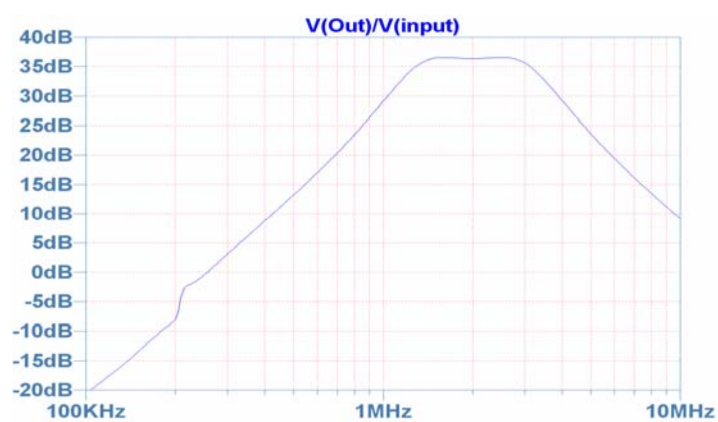


Figure 5 – Frequency response

5. Output matching capacitor (C1)

The output matching capacitor C_1 is a sensitive device that has to stand high RF voltage (8 kV) and current (70 A). For reliable operation the design voltage is assumed to be 12 kV. The construction will use a coaxial geometry (fig.6) with Teflon isolation (to limit the dissipated power) between the cylinders and if needed, the terminations will be covered with araldite. The loss factor of Teflon at 1 MHz is

$$\tan\delta \approx 0.0002$$

For the required capacitance (700 pF) the equivalent series resistance and the power dissipated in the capacitor are

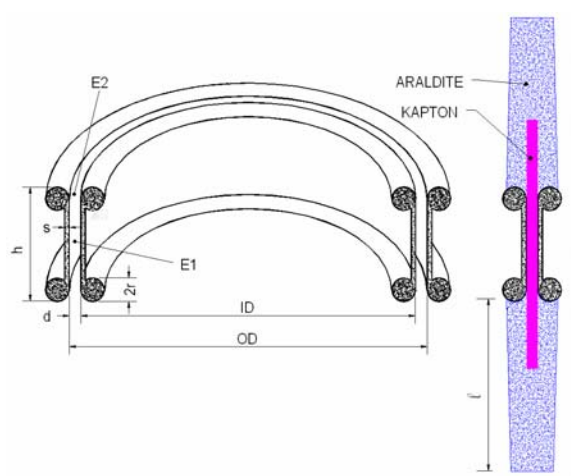
$$R_S = \frac{\tan\delta}{\omega \cdot C} \approx 0.025 \quad [\Omega]$$

$$P_C = \frac{I^2 \cdot R_S}{2} \cdot \left(\frac{t_P}{t_{REP}}\right) \approx \frac{70^2 \cdot 0.025}{2} \cdot \left(\frac{1ms}{20ms}\right) \approx 3 \quad [\mathrm{W}]$$

The electric fields involved in the structure will be kept around 70 % of the maximum admissible for Teflon (23.6 kV/mm) and the araldite will provide a discharge path such that the surface field will stay below the standard design limit of 500 V/mm. The following table lists the dimensions and parameters for the capacitor:

Table 3 – Capacitors parameters (fields for 200 kV applied voltage)

C [pF]	E_1 [kV/mm]	E_2 [kV/mm]	s [mm]	ℓ [mm]	h [mm]	ID [mm]	OD [mm]	d [mm]	r [mm]
700	17.3	16.5	5	15	94	89.3	90.7	0.7	2.5



Field in the central region:

$$E_1 \approx \frac{V}{\frac{ID}{2} \cdot \ln\frac{OD}{ID}}$$

Field at the terminations:

$$E_2 \approx \frac{0.45 \cdot V}{r \cdot \ln\frac{r + d/2}{r}}$$

Capacitance

$$C \approx \varepsilon_0 \cdot \varepsilon_r \cdot \frac{\pi \cdot (ID + d) \cdot (h - 2 \cdot r)}{d}$$

h and $r >> d$;

Figure 6 – Capacitor structure and parameters

The two cylinders will be assembled by heating the external one so as to exploit the thermal dilatation. A minimum change in diameter $\Delta OD=0.7$ mm is required in the assembly operation which takes place in about 2 minutes. The linear thermal expansion of aluminium is $\alpha=23\ 10^{-6}$ so that for a maximum heating temperature $T_{MAX}=350\ °C$ and an ambient temperature $T_{AMB}=20\ °C$, the minimum required value of OD is:

$$OD_{MIN} = \frac{\Delta OD}{\alpha \cdot (T_{MAX} - T_{AMB})} = \frac{0.7}{23 \cdot 10^{-6} \cdot (350-20)} \approx 92\ mm$$

which is compatible with the selected dimensions.
The cooling speed must also be evaluated to ensure enough time for the assembly operation. The cooling law can be expressed as follows:

$$T_t = T_{AMB} + (T_{MAX} - T_{AMB}) \cdot e^{-\frac{k \cdot S_U}{C_{TER}} \cdot t}$$

where:

- k: is thermal conductivity per surface unit from metal to air expressed in kcal/(hour·m^2·K). Typical values range from 3 to 30. Calculations suggest that the value should stay below 10 and for safety $k=20$ has been adopted.
- S_U: exchange surface in m^2
- C_{TH}: thermal capacity (volume·specific weight·specific heat).
  - Al specific weight= 2700 kg/m^3
  - Al specific heat= 0.22 kcal/kg·K

Table 4 lists the parameters used for the calculation and fig.7 show the evolution of dimensions and temperature as function of time.

Table 4 – Capacitors parameters for cooling time calculations

C [pF]	**s [mm]**	**h [mm]**	**OD [mm]**	**r [mm]**	**S_U [m^2]**	**Vol [m^3]**	**C_{TH} [kcal/K]**	***k***	**T_{MAX} for ΔOD=0.5 mm after 2 min. cooling [°C]**
700	5	94	90.7	2.5	0.246	$1.12 \cdot 10^{-3}$	0.665	20	265

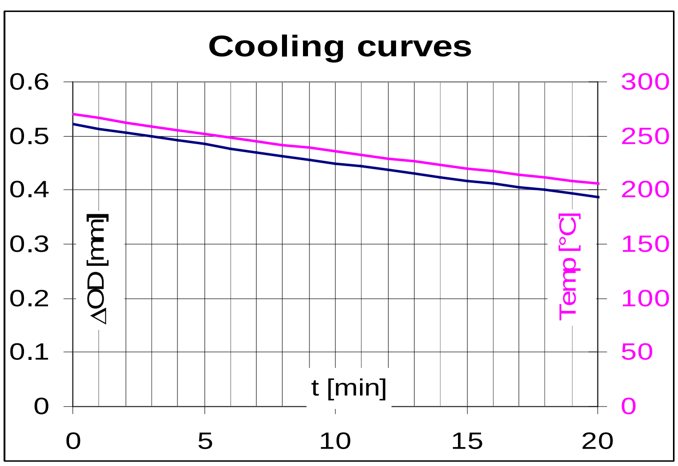


Figure 7 – Capacitor temperature and ΔOD vs. time

6. DRIVER CHAIN, REGULATION AND PROTECTIONS

A dedicated RF generator will produce the excitation signal that will be amplitude modulated according to the control signal generated by the AVC Loop electronics. When triggered, this module will establish the RF signal at the amplitude defined by 'P FWD' reference. Should the reflected power reach the limit set by the 'P REF' reference, the driving signal amplitude will be limited so as not to exceed the limit. The resulting RF signal will then be boosted by 4 W (PS/RF-HC3331) and a 100W (EDA-00099) amplifiers before the power stage.
The final stage will also be protected against cathode over-currents. This interlock rapidly (<100µs) acting on the screen grid bias, the 100 W driver gain and the AVC Loop electronics, will automatically reset before the next trigger pulse.

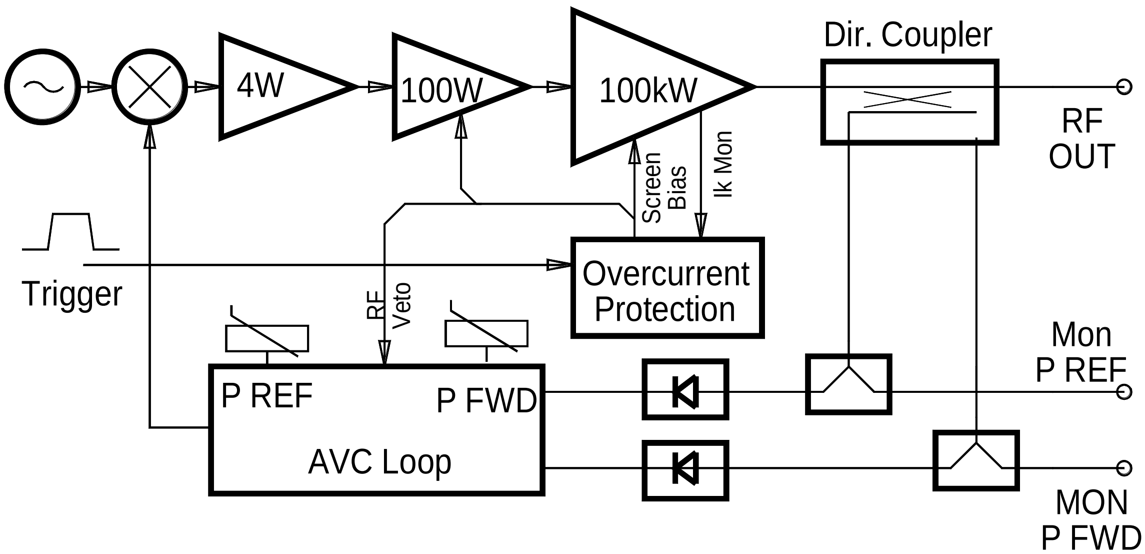


Figure 8 – Regulation and protections block diagram